Oklahoma Earthquakes: Risks for the State and Industry

TODD HALIHAN, PH.D., P.GP.

PROFESSOR

OKLAHOMA STATE UNIVERSITY

BOONE PICKENS SCHOOL OF GEOLOGY

Tuesday, 28 October 2014

The new normal in technology development?

0% Risk

blog.nature.org

Technical Reality

100% Risk

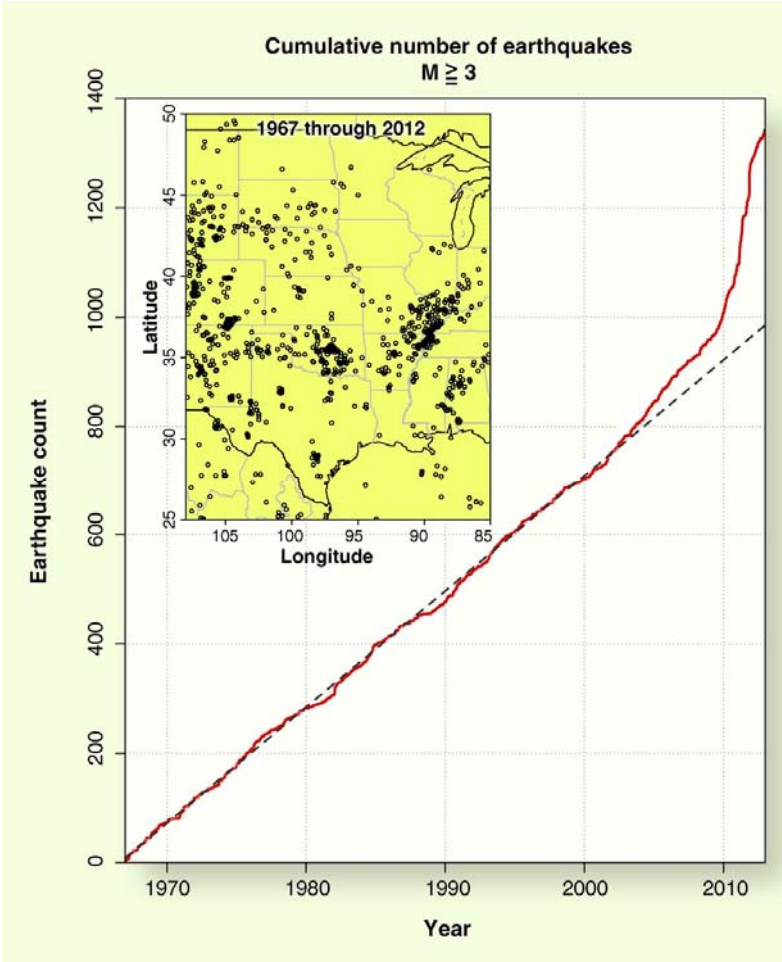
e-multiweb.com

Science Summary I: Problem Exists

"probability of missing $M \geq 3$ earthquakes …has been near zero for decades"

"Understanding which earthquakes may have been induced and, if so, how are challenging problems to solve in the current data-poor environment."

(Ellsworth, 2013: Central U.S.)



Science Summary II: Likely Cause

"seismicity in central Oklahoma has increased dramatically starting in 2009, an increase that is inconsistent with any natural processes that are likely to occur in this geologically stable area."

"For central Oklahoma, it appears more likely that the remarkable increase in seismicity is the result of deep injection of wastewater associated with the rapid growth of oil and gas production"

(McGarr, 2014)

Science Summary III: Mechanism

Injection induced seismicity is a mechanism tested "beyond reasonable doubt"

(Rayleigh et al., 1976: Rangely, CO)

"injection-triggered earthquakes are more common than is generally recognized"

"earthquakes are more likely to be triggered if injection reaches a critical rate, this critical rate may well depend on local subsurface conditions and thus vary in different geographic regions."

(Frohlich, 2012: Barnett Shale, TX)

Science Summary IV: Oklahoma

Oklahoma is not following injection protocols designed to prevent induced seismicity

(Davis and Frohlich, 1993; National Research Council of the National Academies, 2012)

Available scientific evidence indicate high volume class II waste disposal wells generate earthquakes in Oklahoma

(Keranen et al., 2014; McGarr, 2014)

Available scientific evidence indicate only a limited number of wells are a problem

(Frohlich, 2012; Keranen et al., 2014)

Outline

1. Qualifications/What is an Expert?
2. Science items: I-IV
3. What are some remaining unknowns?
4. My concerns?

What is an expert?

Daubert Standard (Daubert v. Merrell Dow Pharmaceuticals)

- Expert Gatekeeper Standard for courts
- Four factors for assessment
  1. **Theory Tested**
  2. **Peer Review/Scientific Journals**
  3. Rate of Error in Evaluation Technique
  4. General Acceptance of Theory

GE v Joiner – Judge can decide expert testimony has gaps

Kumho Tire Co. v. Carmichael – judge gatekeeping extends to non-scientific expert evidence

Expertise Required

1. Geophysics
2. Hydrogeology
3. Industry Experience
   - Petroleum
   - Environmental
4. Local Knowledge of Geology

Halihan, Ph.D., P.Gp. Overview

- B.A. Physics
- M.S. Geosciences
- Ph.D. Geosciences

- Professor, OSU Geology
- CTO, Hydrogeophysics Firm
- Registered Professional Geophysicist (CA)

- Associated Editor for scientific journal, *Ground Water*
- Chair, Geological Society of America, Hydrogeology Division
- Oklahoma Water Resources Board, Arbuckle-Simpson Study Technical Peer Review Team
- Teach *Integrated Petroleum Water Resources Management*

Outline

1. Qualifications/What is an Expert?
2. Science items: I-IV (Number I and II)
3. What are some remaining unknowns?
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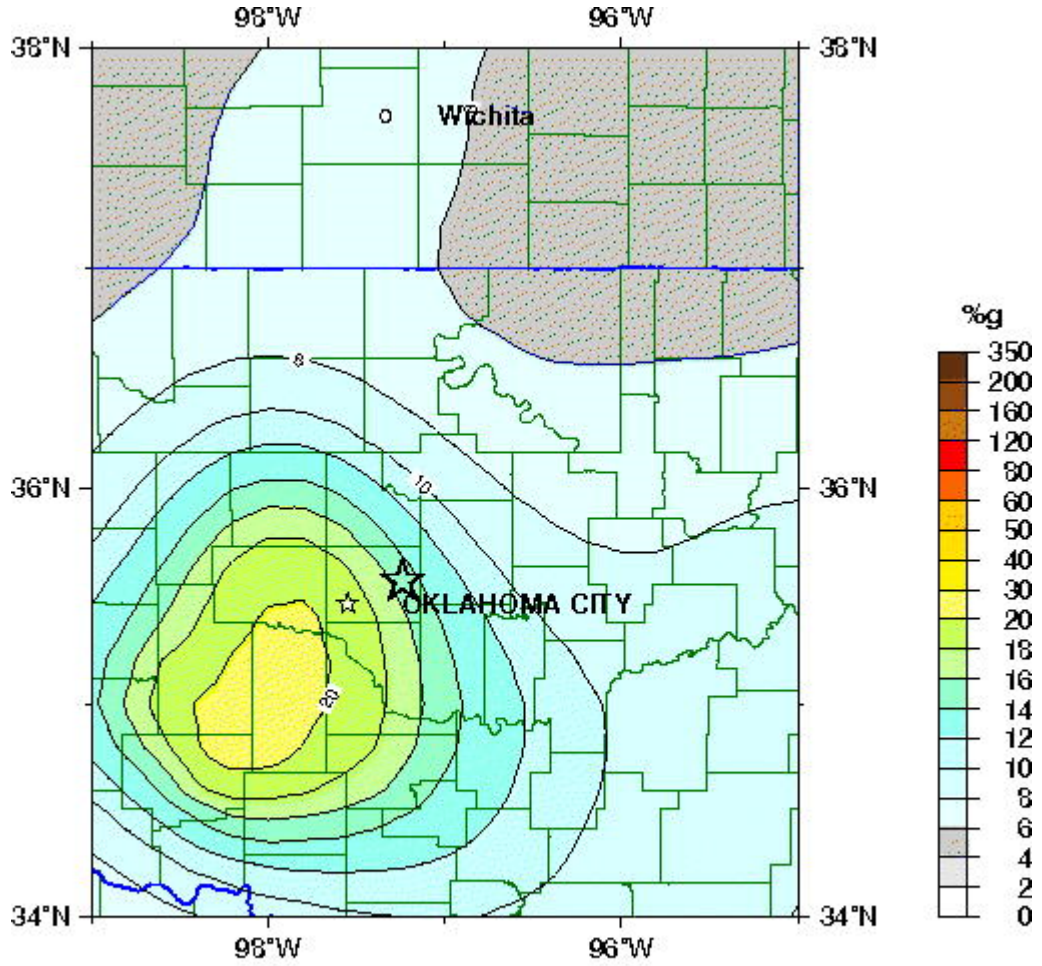
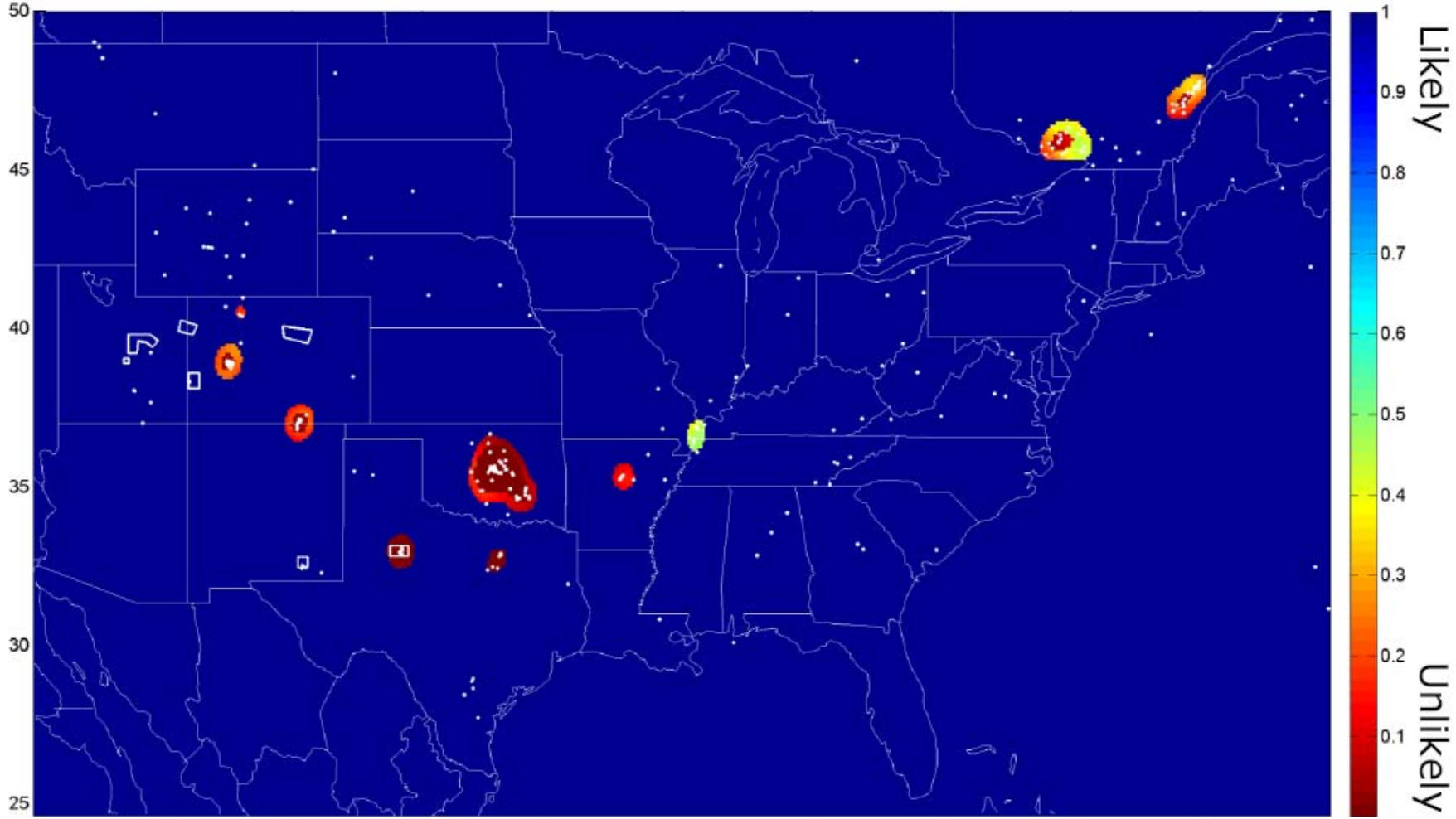
2008 Seismic Risk Map for OK

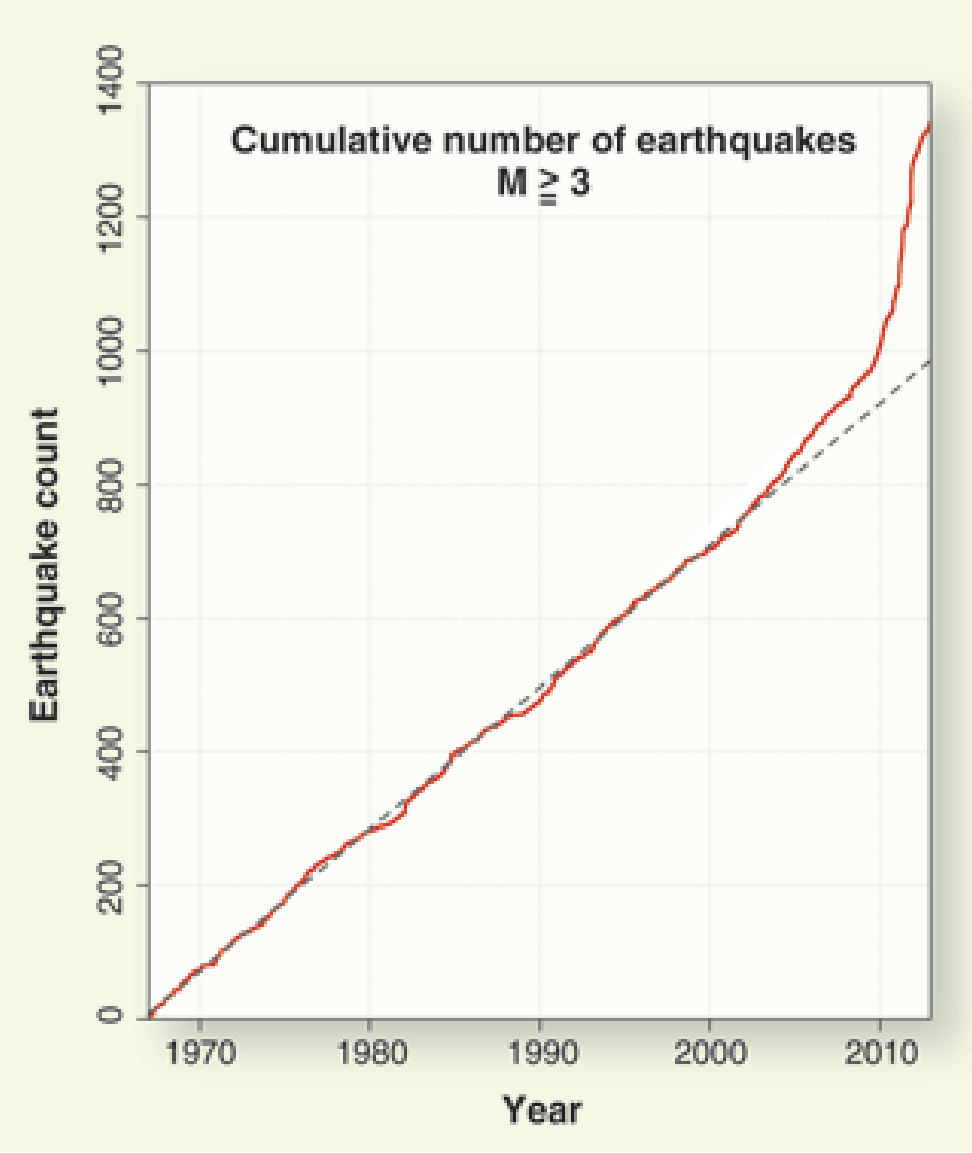


Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project

Areas with anomalous numbers of earthquakes in 2009-2012 relative to the forecast of the 2008 National Seismic Hazard Map



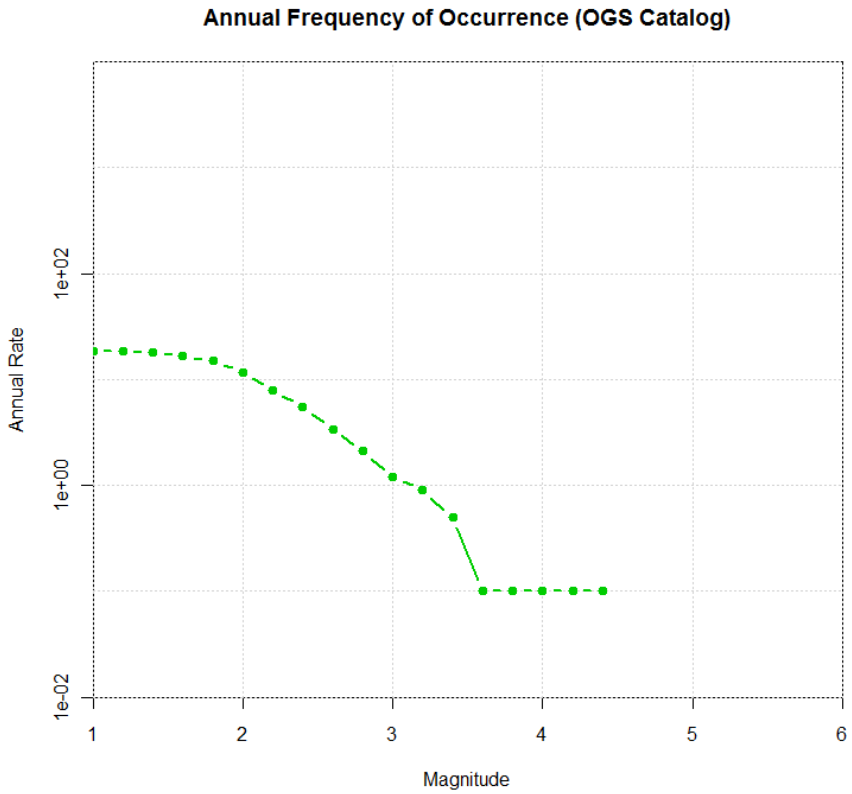
Llenos, A. L., J. L. Rubinstein, W. L. Ellsworth, C. S. Mueller, A. J. Michael, A. McGarr, M. D. Petersen, M. Weingarten, and A. A. Holland (2014), Increased earthquake rates in the central and eastern US portend higher earthquake hazards, Southern California Earthquake Center Annual Meeting, Palm Springs, CA.

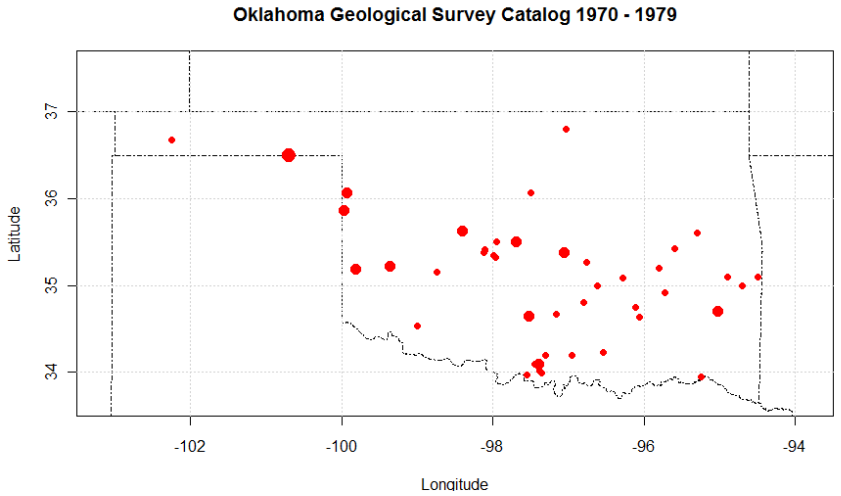


Earthquakes with magnitude (M) ≥ 3 in the U.S. midcontinent, 1967–2012. After decades of a steady earthquake rate (average of 21 events/year), activity increased starting in 2001 and peaked at 188 earthquakes in 2011. Human-induced earthquakes are suspected to be partially responsible for the increase.

Ellsworth, W.L., 2013, Injection-Induced Earthquakes, Science, v. 341, no. 6142, DOI: 10.1126/science.1225942

1970 - 1979

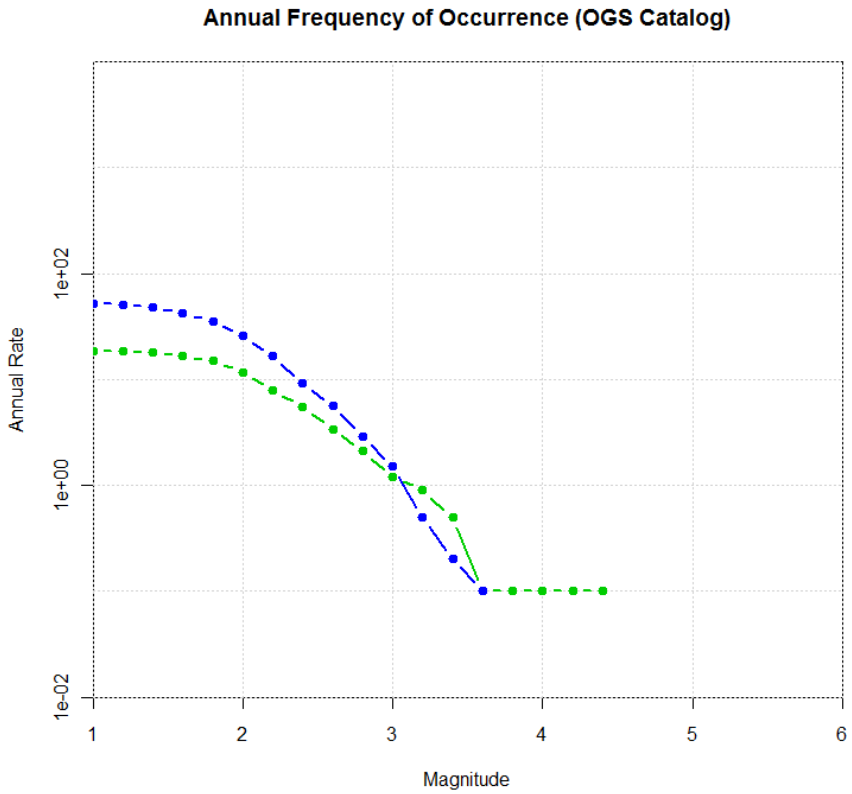


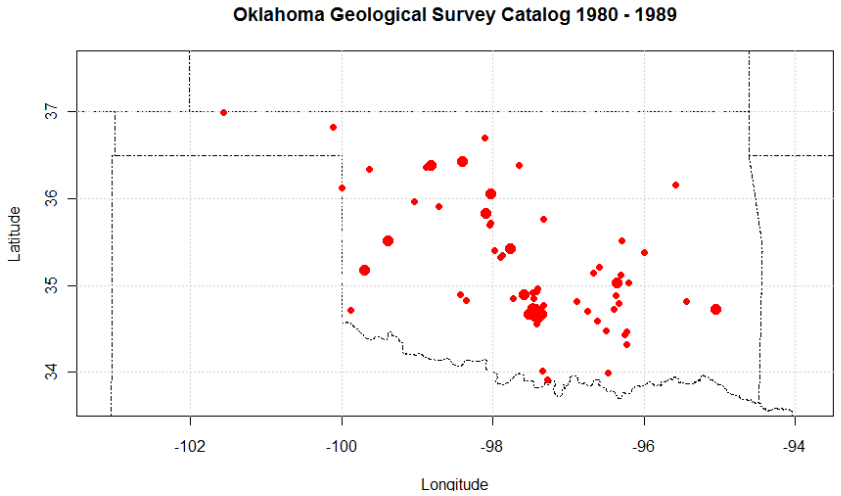


P(one or more) = 1 – exp(-(Annual Rate) t)

Provided by W. Ellsworth, USGS

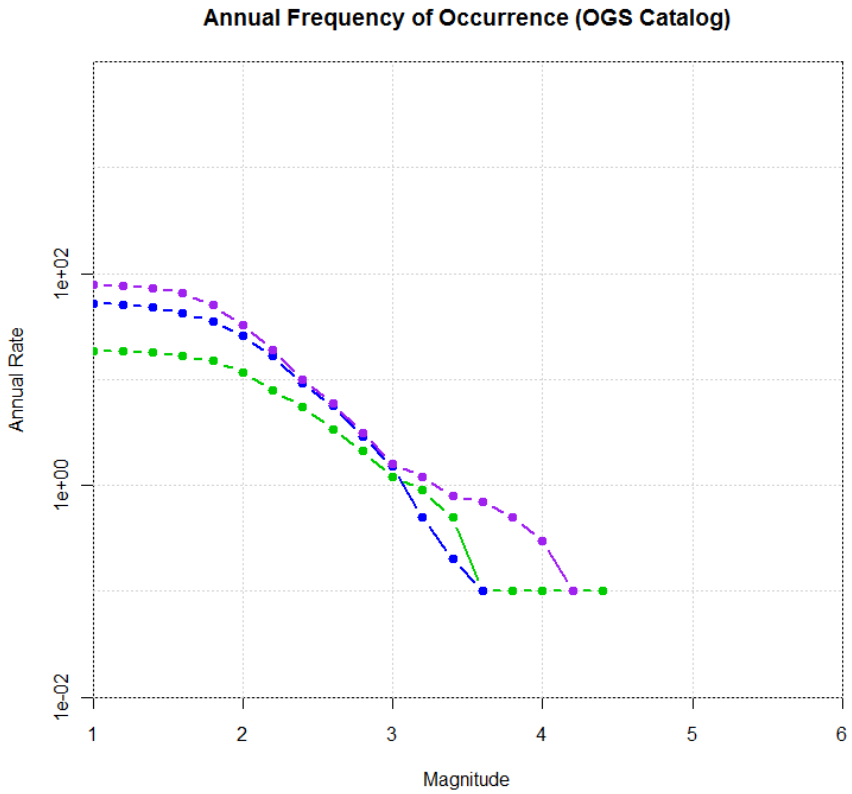
1980 - 1989

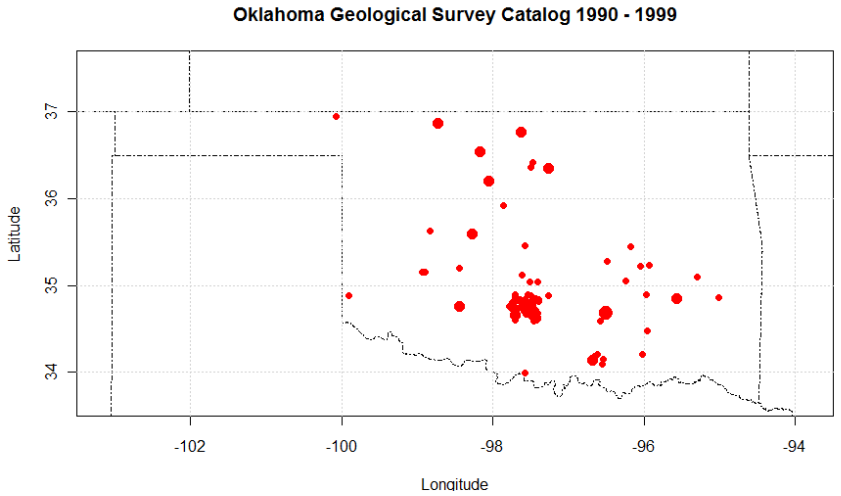




Provided by W. Ellsworth, USGS

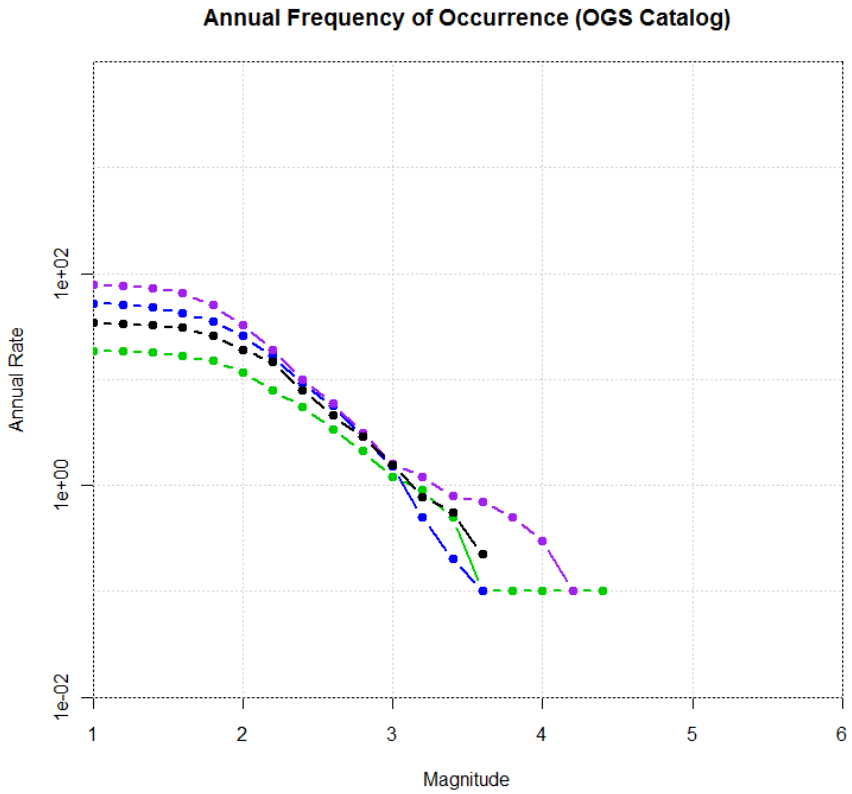
1990 - 1999

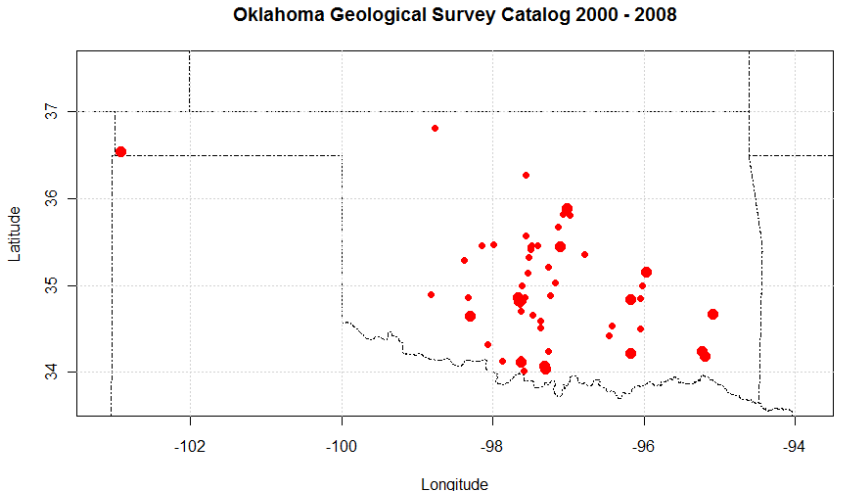




Provided by W. Ellsworth, USGS

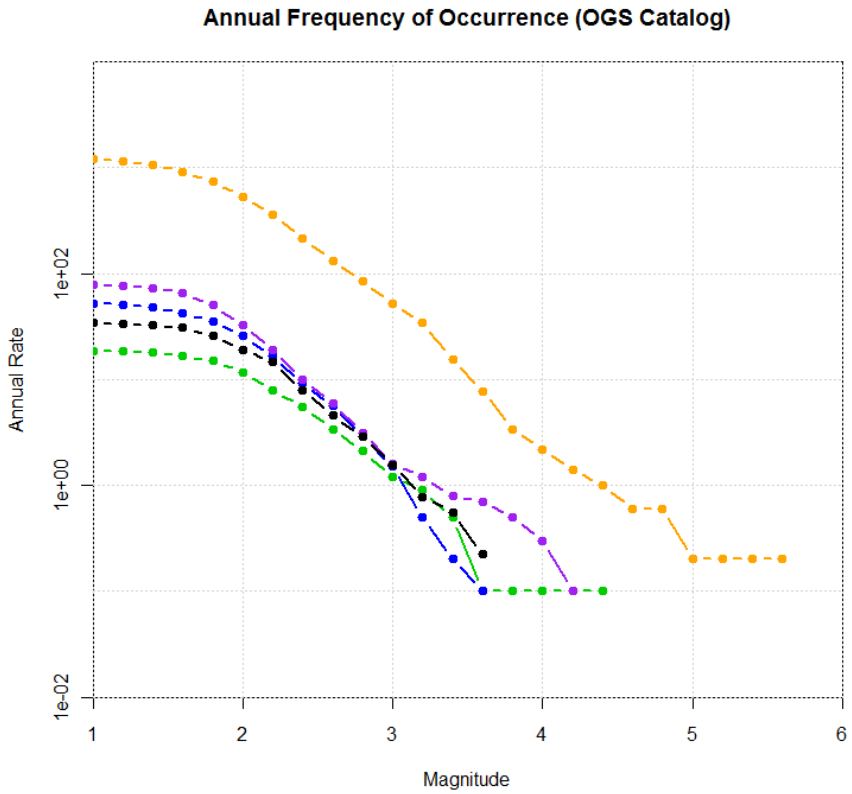
2000 - 2008

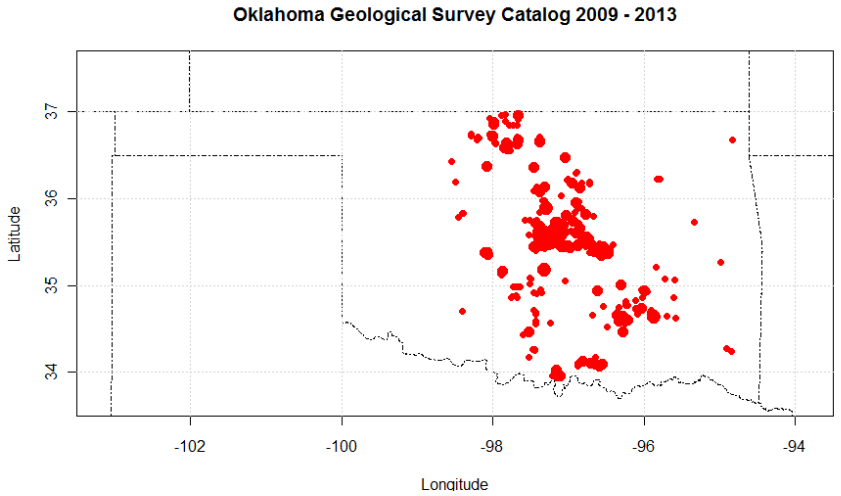




Provided by W. Ellsworth, USGS

2009 - 2013





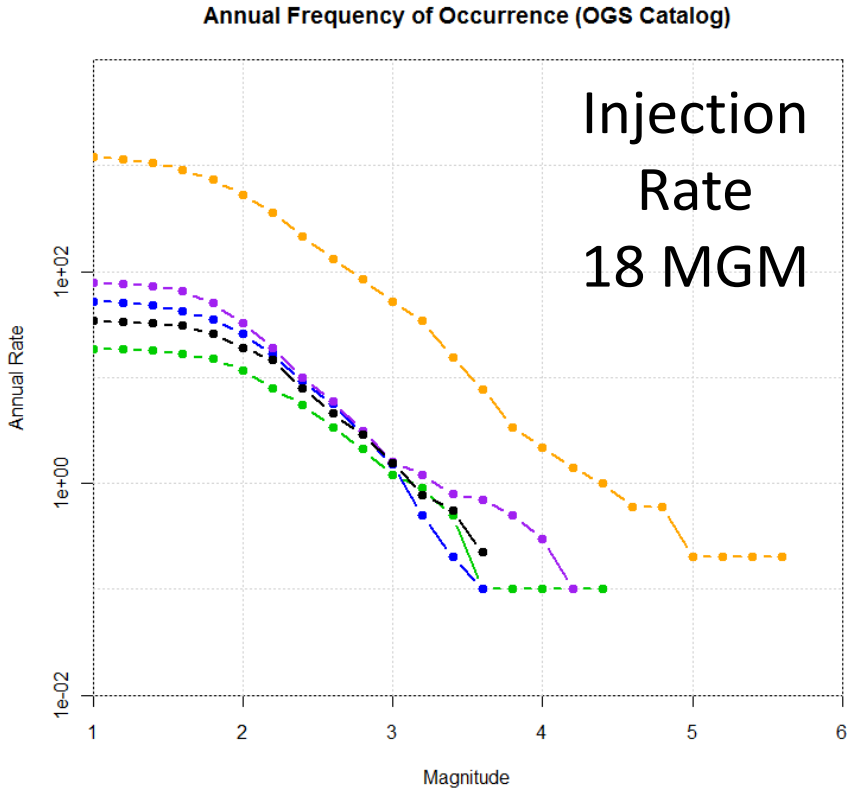
Provided by W. Ellsworth, USGS

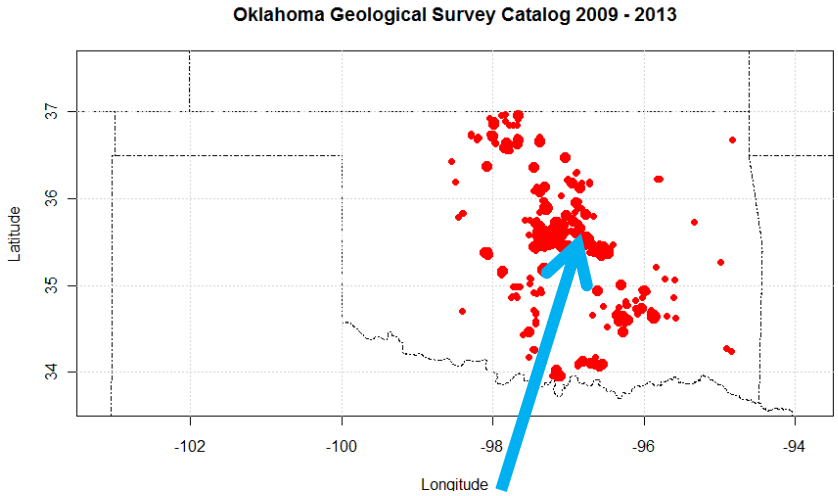
Waste water injection

Keller, G. R., and A. Holland (2013), Oklahoma Geological Survey evaluation of the Prague earthquake sequence of 2011. [Available at http://www.ogs.ou.edu/earthquakes/OGS_PragueStatement201303.pdf.]

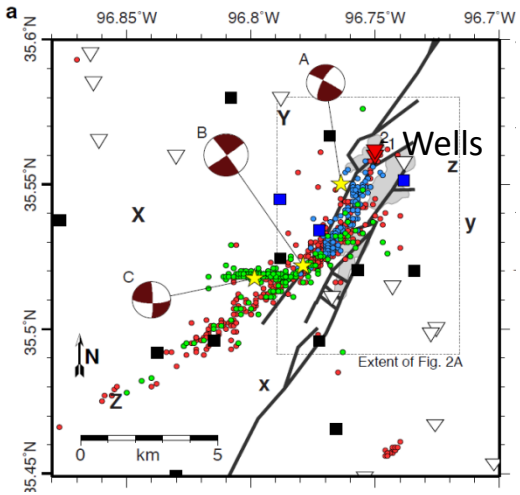
McGarr, A. (2014), Maximum magnitude earthquakes induced by fluid injection, J. Geophys. Res. Solid Earth, 119, 1008–1019, doi:10.1002/2013JB010597.

2009 - 2013





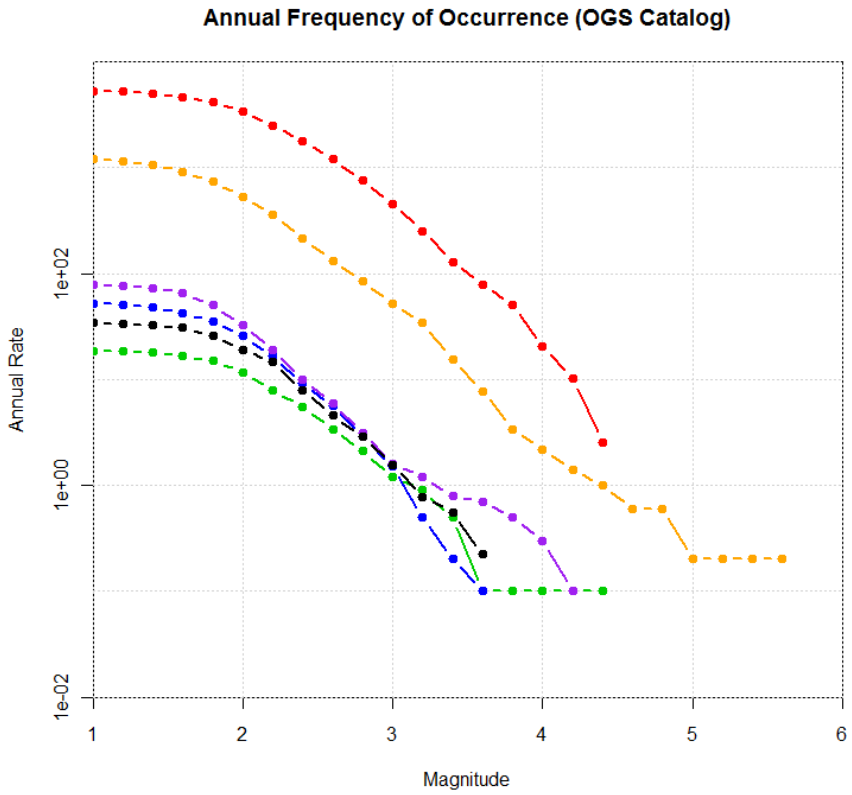
M_w 5.7 Prague, OK

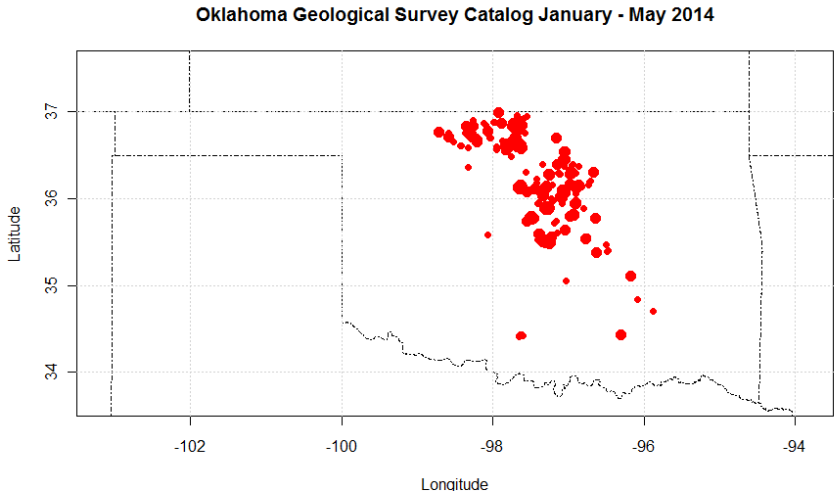


Keranen, K.M., Savage, H.M., Abers, J.A., and Cochran, E.S., 2013, *Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence, Geology*., doi:10.1130/G34045.1

Provided by W. Ellsworth, USGS

2014 to May





P(M≥5½) = 0.23 to 0.53
in the next 12 months

Compared with the 1970-2008
expectation of
P(M≥5½) = 0.003

Provided by W. Ellsworth, USGS

USGS
science for a changing world

OKLAHOMA GEOLOGICAL SURVEY 1908

Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes

Updated USGS-Oklahoma Geological Survey Joint Statement on Oklahoma Earthquakes

Originally Released: 10/22/2013 1:07:59 PM; **Updated May 2, 2014**

The rate of earthquakes in Oklahoma has increased remarkably since October 2013–by about 50 percent – significantly increasing the chance for a damaging magnitude 5.5 or greater quake in central Oklahoma.

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significantly increasing the chance for a damaging magnitude 5.5 or greater quake in central Oklahoma.

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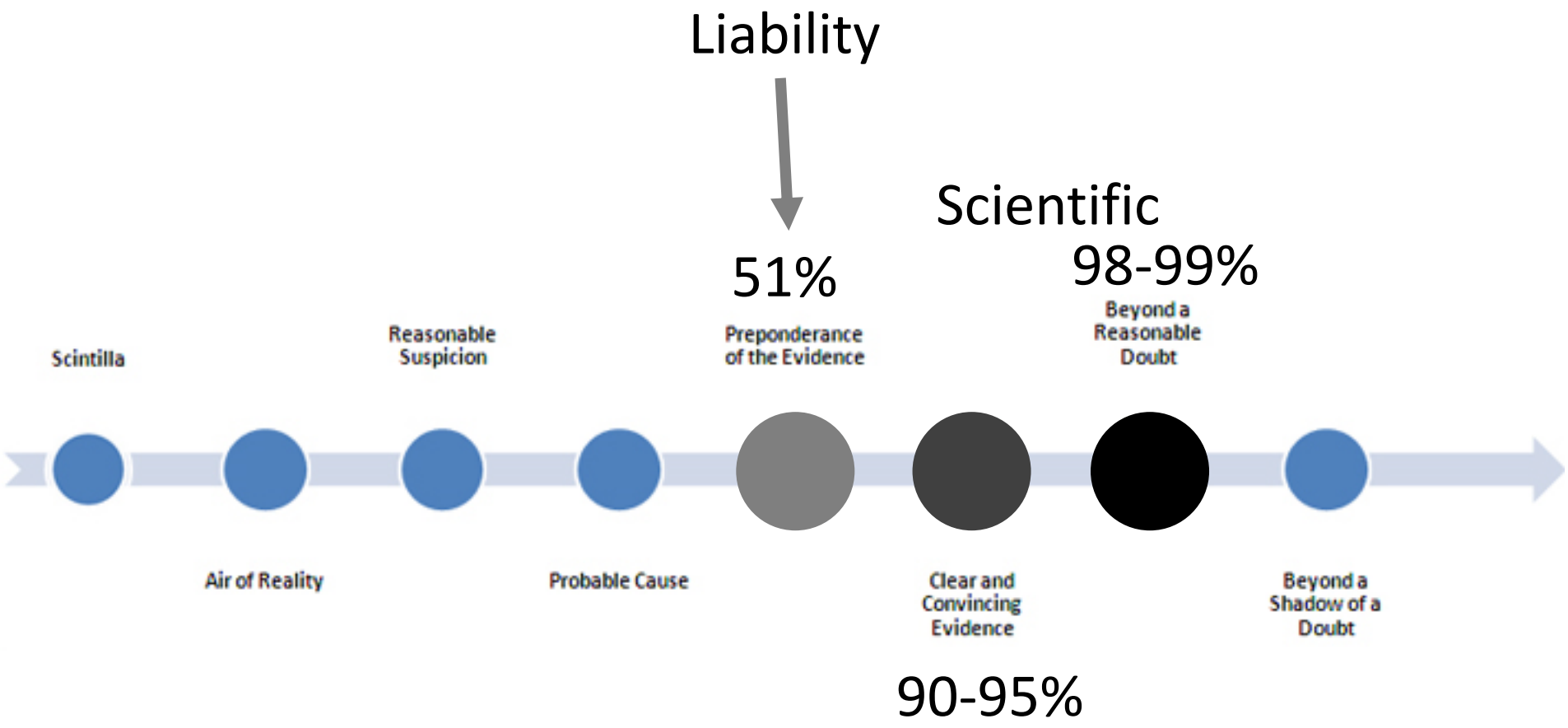


http://defensewiki.ibj.org/index.php/Standards_of_Proof

Some Known Induced Seismicity Mechanisms

1890s – South African mine seismicity

1920s – Petroleum production seismicity

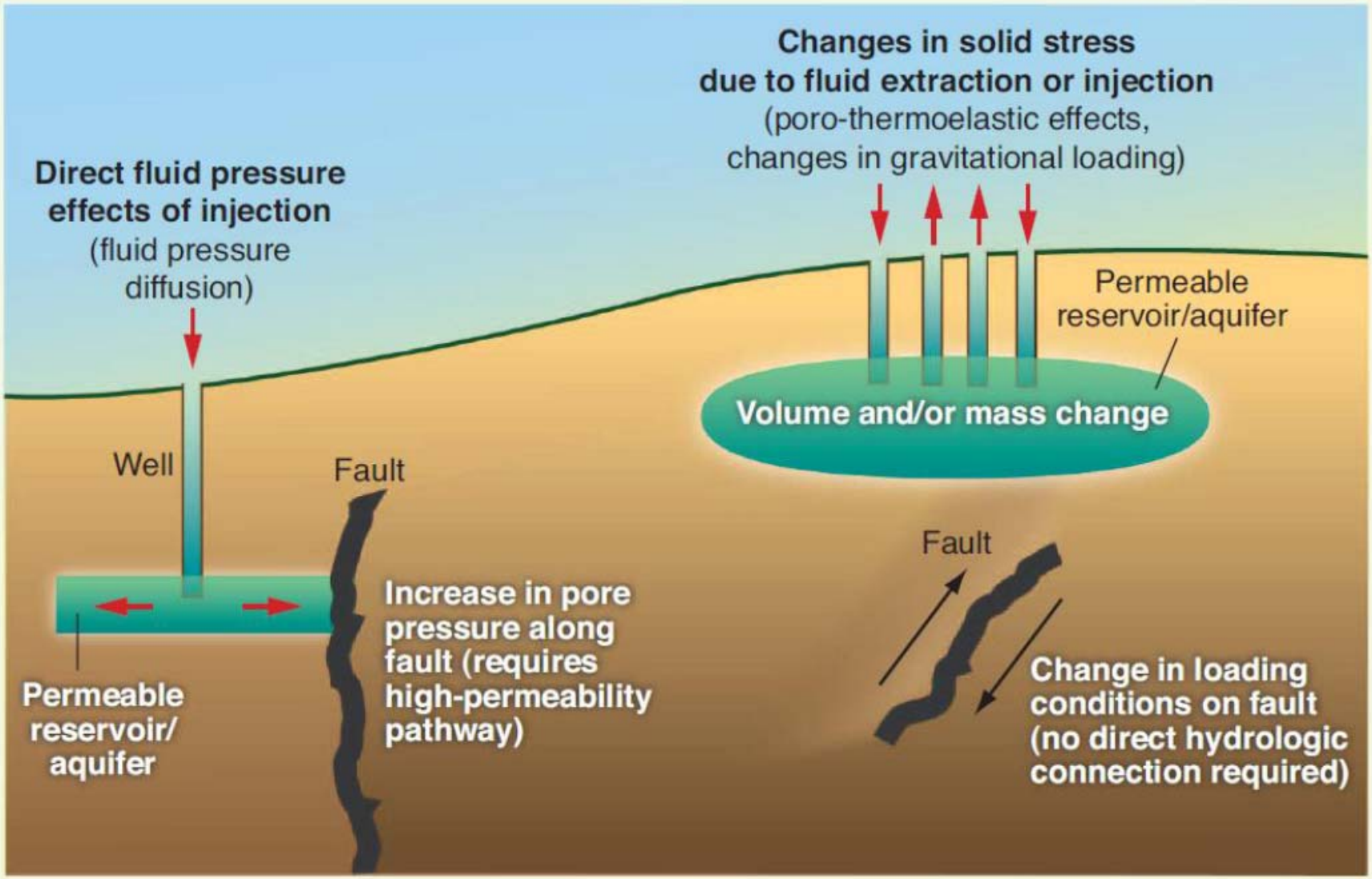
1930s – Surface reservoir seismicity

1960s – Injection seismicity

1960s – Natural gas production seismicity

McGarr et al, 2002

Mechanics of induced earthquakes



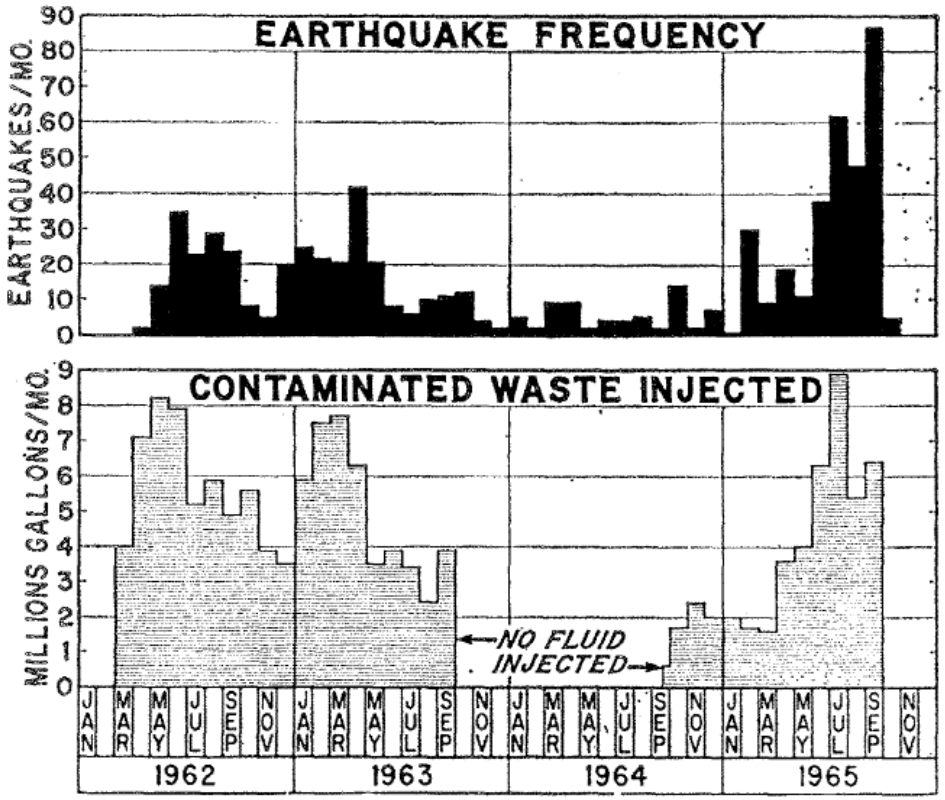
Ellsworth, 2013

Injection Induced Seismicity Rocky Mountain Arsenal, CO

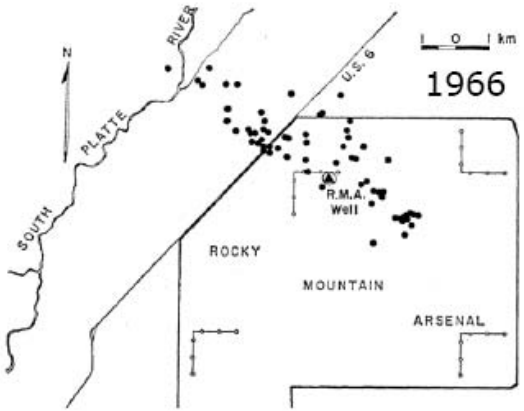
"The disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, CO."

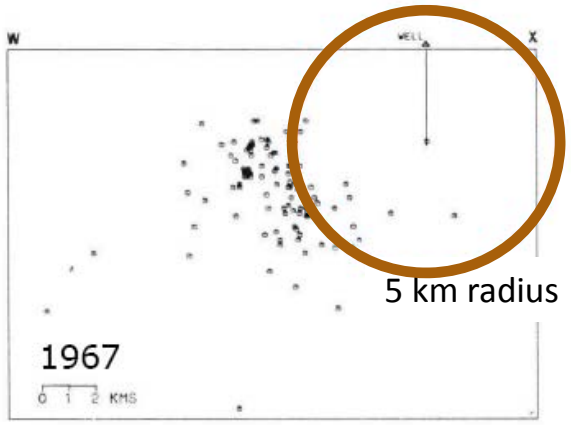
Healy, J.H., Rubey, W.W., Griggs, D.T. and Raleigh, C.B., 1968, The Denver Earthquakes; Science, v. 161, p. 1301-1310.

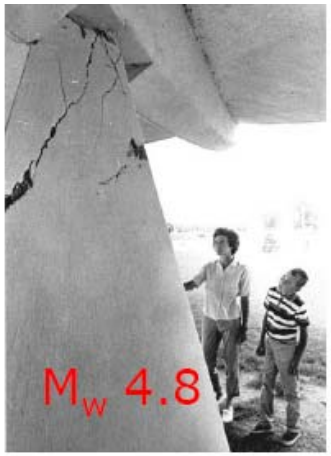
Injection Rate 4 MGM



RMA Earthquakes







Relocations by Herrmann & Park (1981)

Largest quake (4.8) after injection ceased

Fault >10 km from injection point

Quakes centered well

Quakes continued for ~15 years post injection

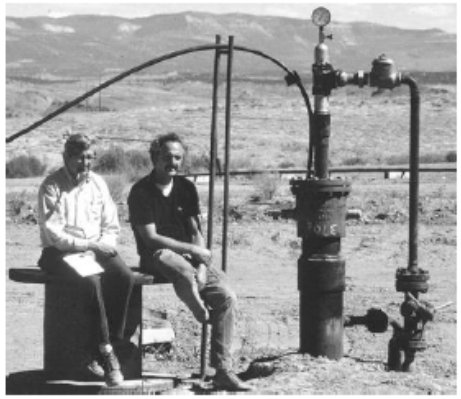
Healy, J.H., et al., 1968

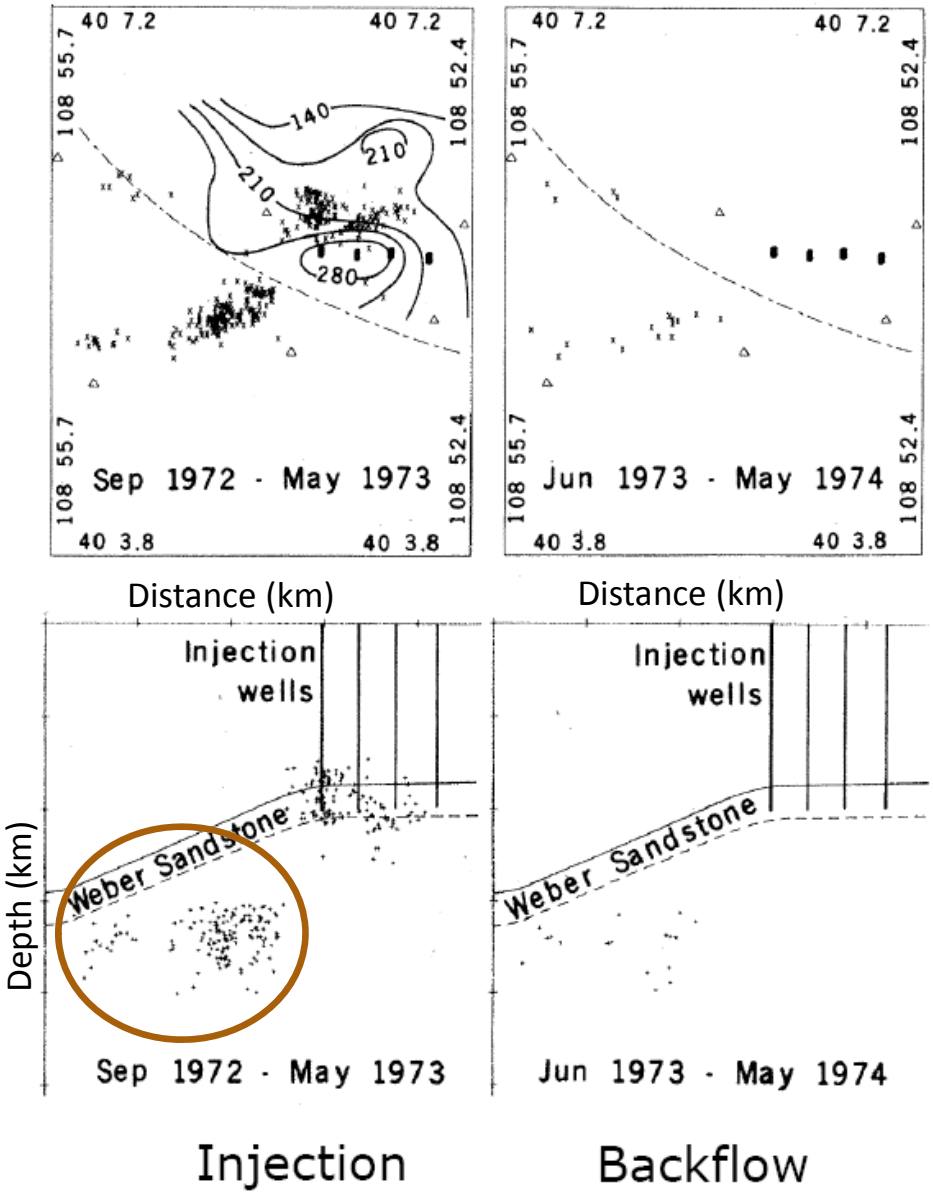
A Test of the Effective Stress Hypothesis at Rangely, Colorado

"Established the correlation between fluid pressure and earthquakes beyond a reasonable doubt"

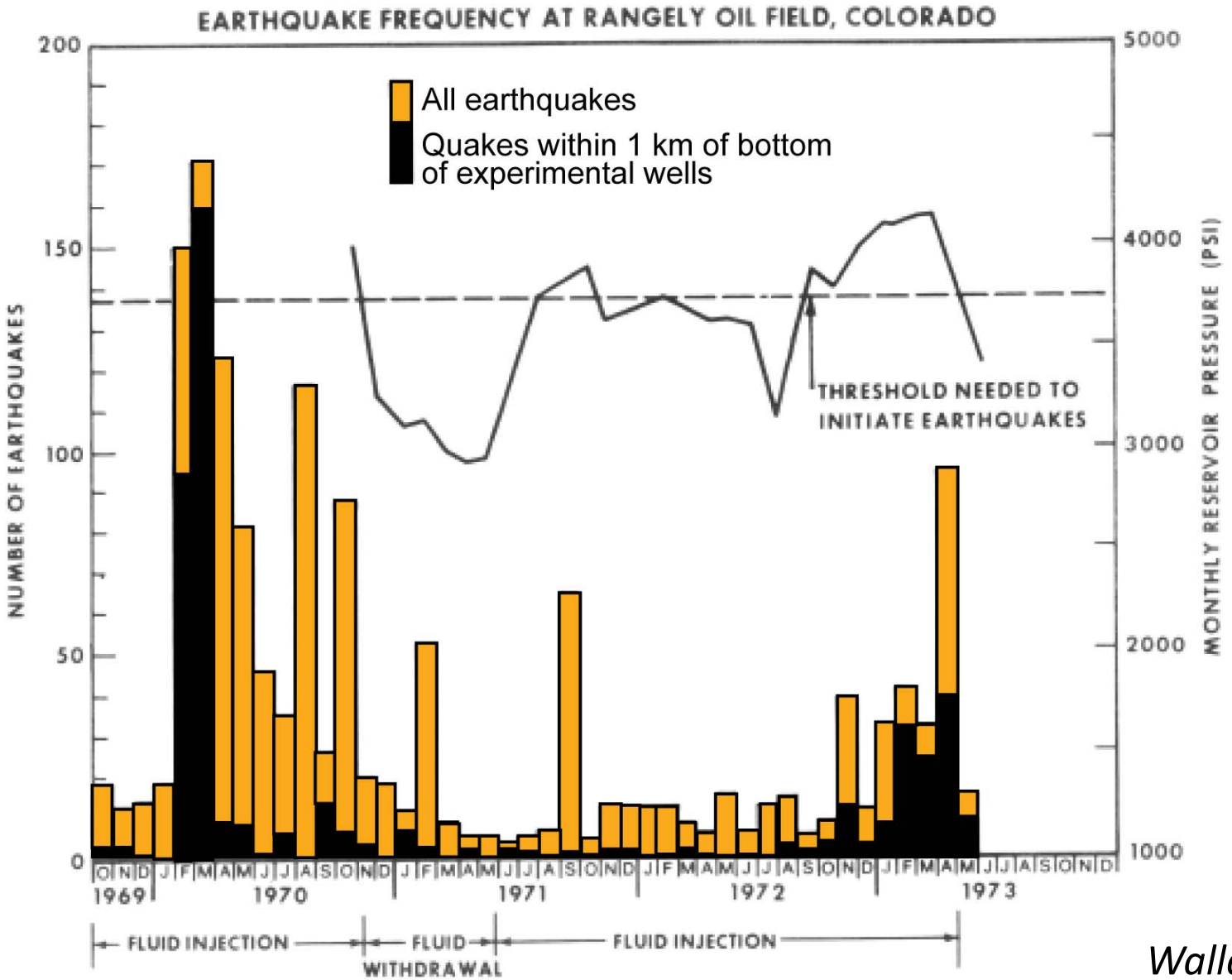
Raleigh, C.B., Healy, J.H. and Bredehoeft, J.T, 1976, *An Experiment in Earthquake Control at Rangely, Colorado; Science,* v. 191, p. 1230-1237.

Injection Rate 2.3 MGM



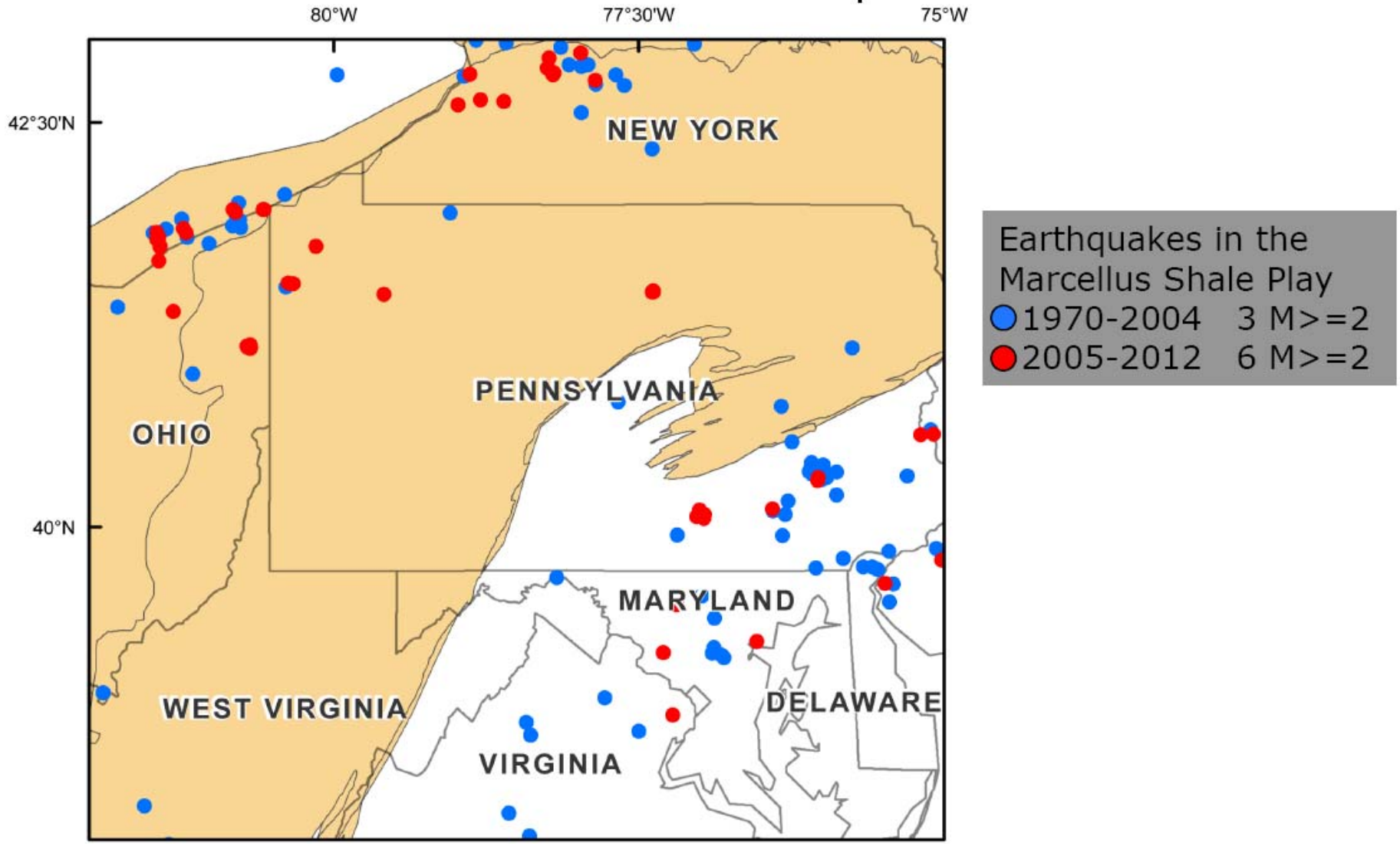


EARTHQUAKE CONTROL



Wallace, 1974

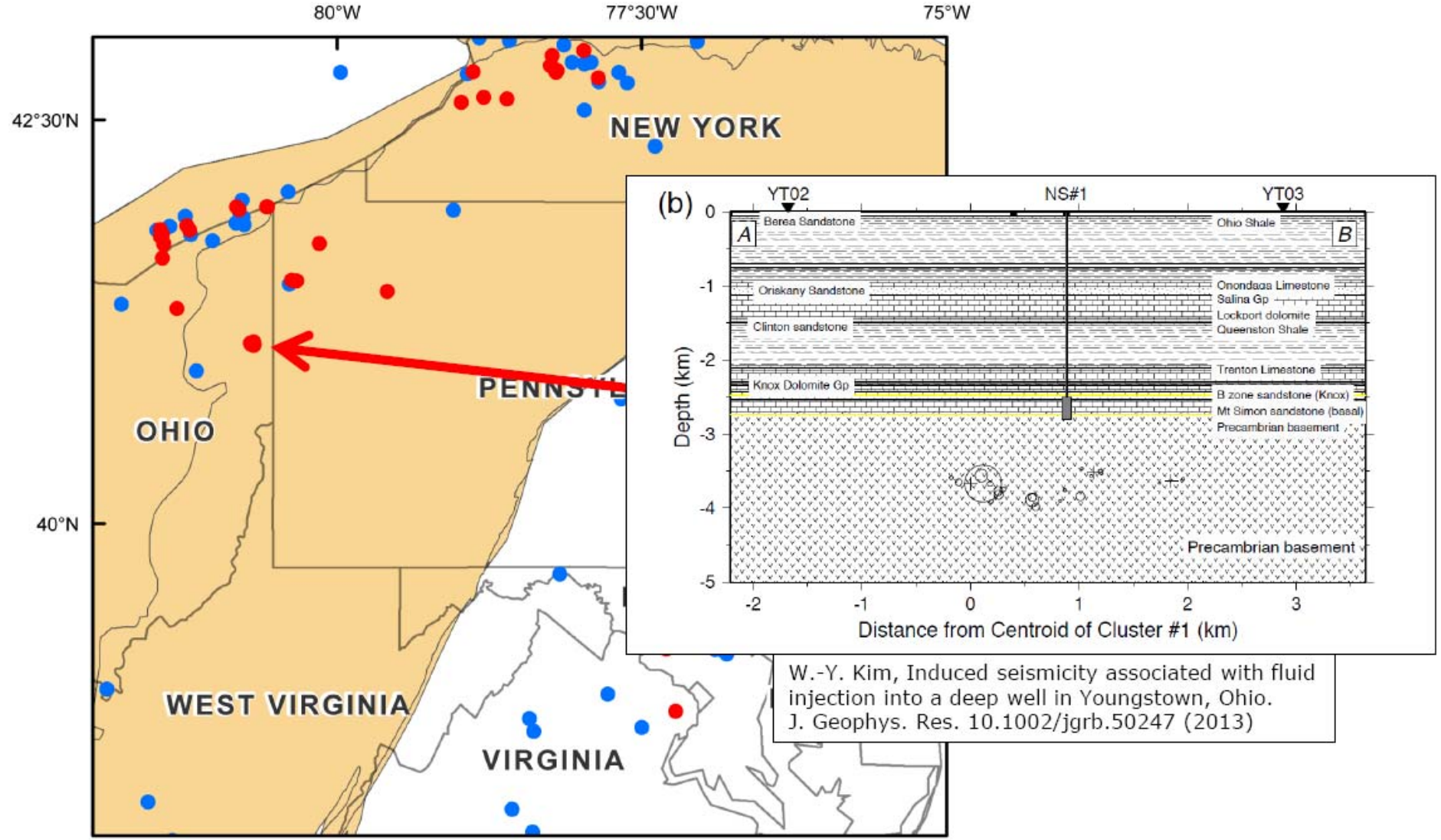
Pennsylvania Earthquakes Before and After Shale Gas Development



LDEO Catalog

Ellsworth, 2013

Youngstown, Ohio M_w 4.0 Earthquake
December 31, 2011



W.-Y. Kim, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. J. Geophys. Res. 10.1002/jgrb.50247 (2013)

Ellsworth, 2013

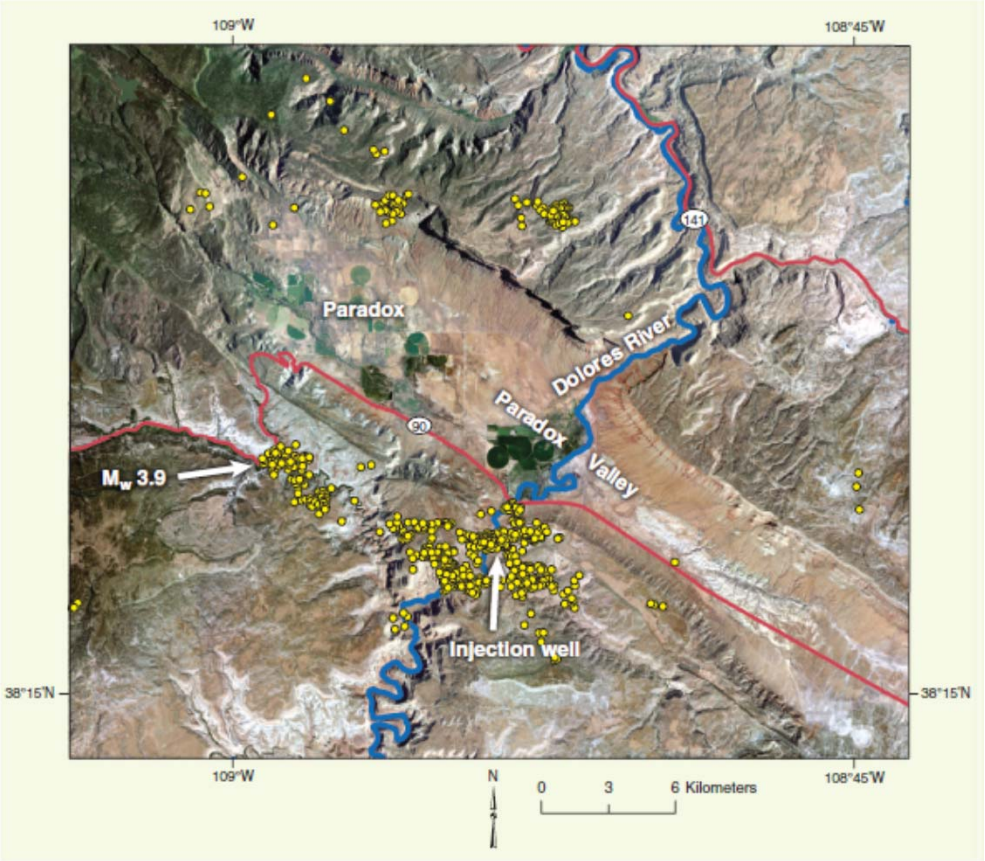
LDEO Catalog

Paradox Valley, CO

Long term injection management since 1996

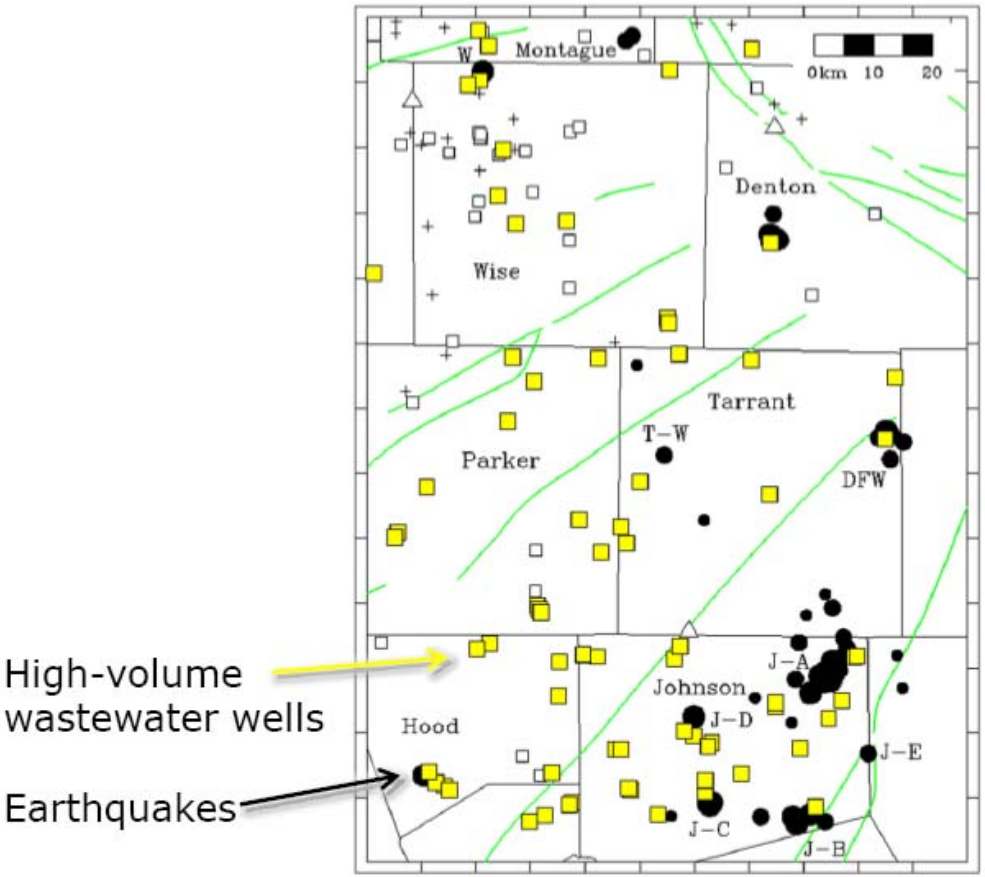
Needed to lower rates several times to reduce seismicity

“long-term, high-volume injection can lead to the continued expansion of the seismically activated region and the triggering of large-magnitude events many kilometers from the injection well”

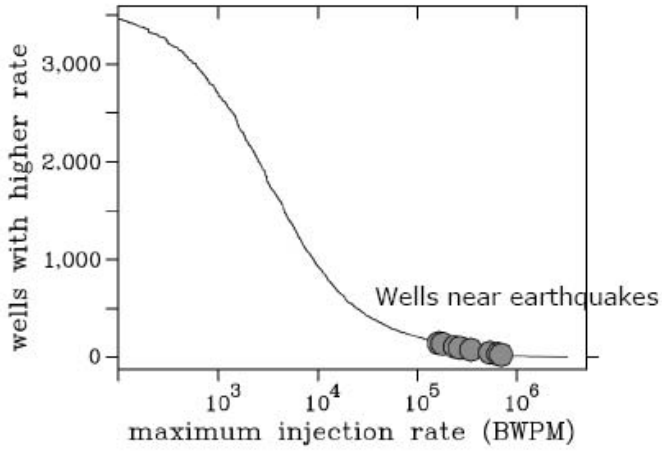


Ellsworth, 2013

Earthquakes and Wastewater in the Barnett Shale



Detailed analysis using USArray Transportable Array showed seismicity to be associated with high-volume waste water injection wells



Frohlich, C., 2012, *Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas*. Proc. Natl. Acad. Sci.

Outline

1. Qualifications/What is an Expert?
2. Science items: I-IV (Number IV)
3. What are some remaining unknowns?
4. My concerns?

Sharp increase in central OK seismicity since 2008 induced by massive wastewater injection

"occur within disposal formations and upper-basement, between 2-5 km depth"

"migrating front of the Jones earthquake swarm …reaches 25 km from the wells by December 2009 and to ~35 km by December 2012."

"Although thousands of disposal wells operate aseismically, four of the highest-rate wells are capable of inducing 20% of 2008-2013 central US seismicity"

Science 25 July 2014:Vol. 345 no. 6195 pp. 448-451
DOI: 10.1126/science.1255802

Induced Seismicity – Fluid Injection for Disposal

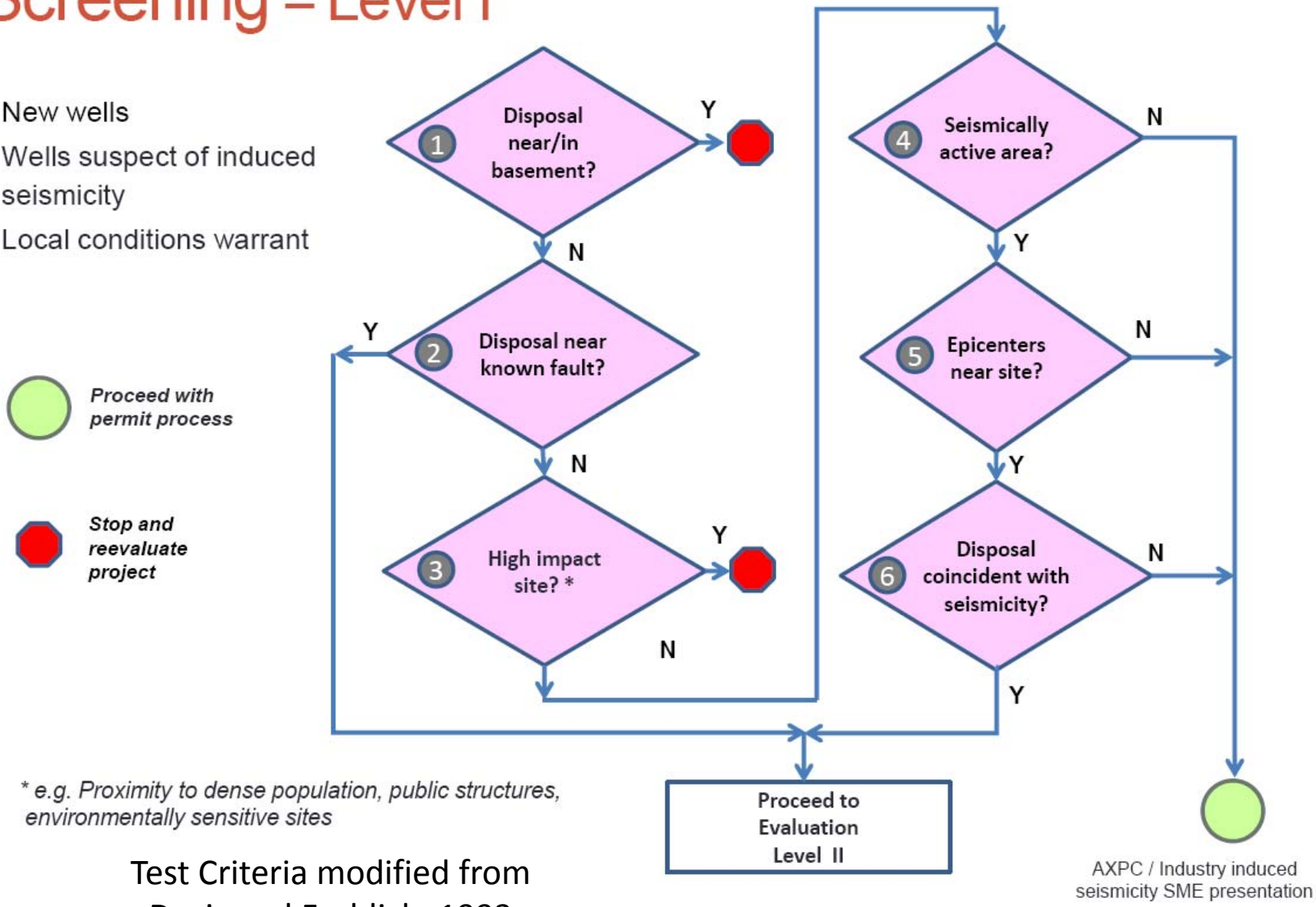
Framework for screening, evaluation, planning, monitoring, mitigation

- Risk management process for fluid disposal wells (UIC Class II)
  - Where significant induced seismicity is suspected and/or concerns due to local conditions – MOST ALL DISPOSAL WELLS HAVE NO SEISMICITY
- Highlights:
  - Proactive approach addressing public and regulatory concerns
  - Screening for siting new disposal wells
  - Not intended for legacy wells not suspected of induced seismicity
  - Scalable process for varying local conditions including: geology, operations, demographics
  - Dynamic – evolves as conditions change
  - Plan for mitigation, if and when, potentially induced seismicity occurs

Jeff Bull, 2013 www.gwpc.org

Screening – Level I

- New wells
- Wells suspect of induced seismicity
- Local conditions warrant



Test Criteria modified from Davis and Frohlich, 1993

Jeff Bull, 2013 www.gwpc.org

Avg. Injection Rates

Site	Avg. Injection Rate (million gal/mo)	Reference
Rocky Mtn Arsenal	4	Healy et al., 1968
Rangely Site	**2.3**	**Gibbs et al., 1972**
Barnett Shale	4	Frohlich, 2012
Prague	18 *(8x)*	McGarr, 2014
Jones	168 *(73x)*	Keranen et al., 2014

Outline

1. Qualifications/What is an Expert?
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Knowns

- Oklahoma seismicity rate is accelerating
  (Ellsworth, 2013)
- Science will not provide any absolutes about single quakes (uncertainty is easy to find)
  (Healey et al, 1968; Rayleigh et al, 1976; McGarr, 2002)
- Extremely difficult scientifically to claim the set of earthquakes in OK is natural
  (Ellsworth, 2013; Keranen, 2013; McGarr, 2014)
- Published scientific evidence of injection induced seismicity mechanism and model for Oklahoma
  (Keranen et al., 2014; McGarr, 2014)

Unknowns

- Where does ~1 Billion Barrels of injected water go each year (~2 Lake Hefners)?
- What does the stress field look like in Oklahoma?
- What does the granitic basement faulting look like? What is the fluid pressure distribution?
- How many illegal injection wells might there be?
- What/when is the largest earthquake going to be?

Options

1. Do nothing: USGS probability analysis of data suggests a significant earthquake is likely

2. Shut down everything: No evidence that is required and will have significant side effects to economy

3. Limit existing high volume injection wells: could determine if earthquake rate slows within 12-24 months, maybe less

My Concerns

We knew the dustbowl would happen scientifically, but as scientists we did not communicate it effectively to the people of the state; I don't want to do it again with a large earthquake

If a damaging earthquake occurs, do the right people foot the bill or do the taxpayers or the companies who are taking the proper precautions foot the bill

Conclusions

I) Problem Exists – increase in seismicity

II) Likely Cause – Class II Injection Disposal Wells

III) Mechanism – Injection Seismicity

IV) Oklahoma – Conditions suitable in OK

Acknowledgements

This talk is a compilation of the research of a large group of people. I have tried to make sure the references are provided for the various pieces. Special thanks go to

William Ellsworth of the USGS,

Katie Keranen of Cornell University,

Tim Sickbert of OK State University,

and Chris Hartnady of Umvoto, Ltd.

Questions?

References

Davis, S.D. and C. Frohlich, 1993, Did (Or Will) Fluid Injection Cause Earthquakes? – Criteria for a Rational Assessment, Seismological Research Letters, v. 64, n. 3-4, p. 207-224, DOI: 10.1785/gssrl.64.3-4.207.

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